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LESSON:

The Biophysics of Hearing Loss

Summary: Students read the article "Decibel Hell: The Effects of Living in a Noisy World" and learn about the everyday contributions of our environment to hearing loss. Students then explore the biophysical mechanisms involved with sound transmission, hearing, and hearing loss. This lesson extends the discussion of a topic addressed within an article in the *EHP Student Edition*.

EHP Article: "Decibel Hell: The Effects of Living in a Noisy World"
EHP Student Edition, April 2005, p. A34–A41
http://ehp.niehs.nih.gov/members/2005/113-1/focus.html

Objectives: By the end of this lesson, students should be able to

1. define wave frequency and amplitude;
2. describe how pressure relates to sound;
3. draw the eardrum, hammer, cochlea, and hair cells;
4. explain the physical and biological processes related to hearing at the macro and cellular levels; and
5. hypothesize about biophysical mechanisms for hearing loss by damage to hair cells.

Class Time: 1 hour if Step 5 is assigned as homework; 1.5 hours if everything is done in class.

Grade Level: 9–12

Subjects Addressed: Anatomy, Physiology, Biology, Physics, Environmental Science, Health

Prepping the Lesson (15 minutes)

INSTRUCTIONS:

1. Obtain a class set of *EHP Student Edition*, April 2005, or download just the article "Decibel Hell: The Effects of Living in a Noisy World" at http://ehp.niehs.nih.gov/members/2005/113-1/focus.html.
2. Review the article as well as the Background Information section and Student Instructions.
3. Make copies of the Student Instructions.
4. Gather plastic containers, drumsticks (or other "drumming" devices such as spoons), and water per group.

MATERIALS:

- 1 copy of *EHP Student Edition*, April 2005, or 1 copy of "Decibel Hell: The Effects of Living in a Noisy World" per student
- 1 copy of Student Instructions per student
- 1 large rectangular (3" x 6" or larger) pliable plastic container (such as a GladWare® disposable container) per group
- 1 drumstick (padded) or wooden spoon per group
- 1 pitcher with water per group

VOCABULARY:

- amplitude
- anvil (incus)
- biophysics
- cochlea
- eardrum
- frequency
- hair cell
- hammer (malleus)
- ions

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- neuron (nerve cell)
- neurotransmitter
- ossicle
- stirrup (stapes)
- stereocilia

BACKGROUND INFORMATION:

Basic information on the physics of sound and the biophysics of hearing are provided in the lesson. Students are introduced to the eardrum, hammer, cochlea, and hair cells in the ear. If you want students to know more about hearing physiology than what is provided here, refer to the Resources section.

Although the lesson relates the amplitude of sound pressure directly to hearing damage, the amount of sound energy (sound pressure squared) is also important. Differences in noise standards often relate to how sound pressure and sound energy are used in calculating the harmful effects of high noise levels.

In addition to introducing students to the basic physics of sound, the lesson introduces hair cell research conducted by physician-scientist Dr. James Hudspeth of Rockefeller University. Scientists have known that the movement of the stereocilia on hair cells from sound input is part of the hearing process, but details of the mechanisms are still being elucidated. In 1964 researcher Dr. A. Flock established that when ciliary bundles on hair cells bent in a certain direction, depolarization or hyperpolarization occurred—i.e., the ion channels in the cells were triggered (Quant Biol 30:133–145). The change in polarization generates the electrical signals that get passed through nerve cells to the brain.

Dr. Hudspeth's research has been focusing on the mechanisms that actually trigger these ion channels. In the 1980s Dr. Hudspeth hypothesized that the hair cell response occurred too quickly for it to be a traditional chemical trigger, as in most cells. So he proposed that the ion channel is turned on from a physical response like a spring pulling open a hatch when the stereocilia bend (http://www.hhmi.org/senses/c120.html). This hypothesis was confirmed with imagery from an electron microscope by a team in England lead by Dr. James Pickles.

Some of Dr. Hudspeth's current work is to identify the mechanism by which attachment points move. His hypothesis is that myosin, the protein that controls muscle contraction, is involved. Understanding the details of these mechanisms may help scientists find ways to improve hearing once it has been damaged or lost. When hearing is damaged from loud noise, the important physical structure of hair cells is compromised, or the hair cell is lost all together. Since human hair cells are unable to repair themselves, hearing losses are irreversible and cumulative. Dr. Hudspeth's work on hair cells over the past 20 years demonstrates the progressive nature of science where one question leads to another in the quest for understanding. Also, many scientists investigate specific steps in a process, such as hearing. The Resources section below provides links to other current hearing research, such the possible use of gene therapy to help people with the regeneration of damaged hair cells (http://www.med.umich.edu/opm/newspage/2003/haircells.htm) or investigating stress-response pathways in the ear following loud noises.

RESOURCES:

Environmental Health Perspectives, Environews by Topic page, http://ehp.niehs.nih.gov. Choose Noise Pollution

Baylor College of Medicine, How the ear works: nature's solution for listening, http://www.bcm.edu/oto/research/cochlea/Volta/index.html

Howard Hughes Medical Institute, The quivering bundles that let us hear: signal from a hair cell, http://www.hhmi.org/senses/c110.html

Kresge Hearing Research Institute, University of Michigan Medical School

Auditory anatomy laboratory, http://www.khri.med.umich.edu/research/altschuler_lab/index.shtml

Auditory biochemistry and molecular biology, http://www.khri.med.umich.edu/research/schacht_lab/research.shtml

Research laboratories, http://www.khri.med.umich.edu/research/

National Institutes of Health, Hearing disorders and deafness, http://health.nih.gov/result.asp/309

Neuroscience for Kids, A sense of hearing, http://faculty.washington.edu/chudler/hearing.html

The Physics Classroom, Sound properties and their perception: the human ear, http://www.physicsclassroom.com/Class/sound/U11L2d.html

University College London, Video of a hair cell moving to music, http://www.physiol.ucl.ac.uk/ashmore/ohc2-s.mpg

University of Michigan, Gene therapy triggers growth of new auditory hair cells in mammals, http://www.med.umich.edu/opm/newspage/2003/haircells.htm

Implementing the Lesson

INSTRUCTIONS:
1. Hand out the Student Instructions and the article "Decibel Hell: The Effects of Living in a Noisy World."
2. Have the students read the article.
3. Discuss examples of noise exposures described in the article that may surprise the students or that they may have never previously thought about. For example, the article mentions how peak noise levels at a hospital during morning shift change were at the decibel level of a jackhammer.
4. Have students pay attention to or share some examples of loud noises at your school (e.g., public address system announcements, bells, talking in the cafeteria during lunch or in the halls between class periods) or home (e.g., listening to music with headsets, leaf blowers, lawn mowers, concerts).
5. Introduce the rest of the "Biophysics of Hearing Loss" lesson beginning with Step 2 on the Student Instructions. Inform the students that they will learn about the physics of sound, the physiology of hearing, and the close connections of physics and biology—called biophysics—in the hearing process. Provide additional explanations about the differences between biology and physics if students do not have a clear understanding. For example, physics studies nonliving things, like matter and energy, and, compared to biology, is often more simple to measure. Biology, the study of living organisms, is often complex, with many variables and processes.
6. Inform the students that once hearing is lost, the damaged cells inside the ear do not heal or regenerate. This means people should be aware of sounds they are exposed to and how they can protect themselves. The fact that hair cells in the ear do not regenerate on their own makes scientific research that much more important. Scientists need to understand details of the hearing process in order to find ways to help people with damaged or lost hearing.
7. Separate students into groups. Each group should have a plastic container, drumstick/spoon, and water. Review the instructions for Step 2 as needed.
8. Inform the students whether they will do Step 5 in class or as homework.

NOTES & HELPFUL HINTS:
- A wooden spoon or a drumstick with a padded end is recommended to reduce the loudness of this exercise.
- If you use small, round containers, it is harder for the students to see the waves in the water because of interference. So use a large rectangular container.
- Students may need to kneel down or change the angle they look at the water to see the waves better.
- If you have access to a sound meter, have students keep track of loud sounds they are exposed to while in school or at home.
- This lesson is an excellent addition to units on sound, hearing, the nervous system, pressure, or waves.
- If you have access to Slinkys, students can pair up, one at each end of the Slinky. One student holds his/her end still while the second student moves the Slinky slowly, then quickly, to see the changes in wave frequency.

Aligning with Standards

SKILLS USED OR DEVELOPED:
- Classification
- Comprehension (listening, reading)
- Computation
- Critical thinking and response
- Manipulation
- Observation
- Graph reading

SPECIFIC CONTENT ADDRESSED:
- Sound
- Hearing
- Biophysics
- Waves

SCIENCE CONTENT STANDARDS MET:

Unifying Concepts and Processes Standard
- Systems, order, and organization
- Evidence, models, and explanation
- Change, constancy, and measurement
- Form and function

Science As Inquiry Standard
- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

Physical Science Standard
- Structure and properties of matter
- Chemical reactions
- Motions and forces
- Interactions of energy and matter

Life Science Standard
- The cell
- Matter, energy, and organization in living systems

Science in Personal and Social Perspectives Standard
- Personal and community health

Assessing the Lesson

Step 2: a) Have one person in your group hold the plastic container upside-down, while another person hits the bottom (now the top) moderately hard with a drumstick or spoon. Place your hand inside the container, close to where the drumstick is hitting, but without touching the container. Using the space provided below, describe what you feel. (Rotate roles so that each person has a chance to reach inside the container while someone else is drumming.)

Students should describe something about feeling air move past their hand every time the container is hit.

b) Partially fill the container with water (a shallow depth will produce better results). Hold the container so that it does not move, then tap the side of the container slowly. Now tap the side quickly. Using the concept of frequency (see Figure 1, below), describe what happens to the water when you hit the side slowly or quickly. You can think of frequency as the number of waves in a given length of time. (The bottom row of the figure shows a frequency increase compared to the waves in the top row.)

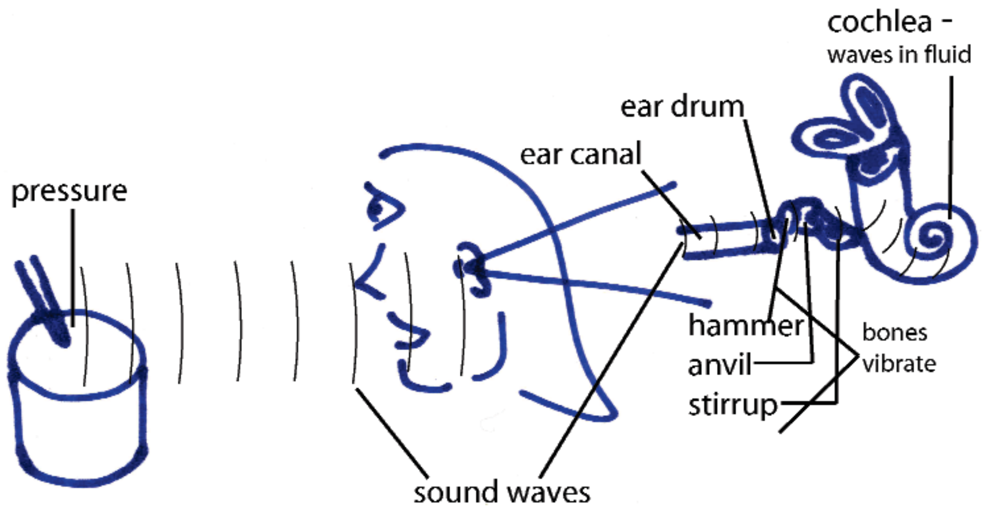
Waves are produced in the water. The frequency of the waves increases when you hit it faster.

c) Hit the side of the container gently once. Observe the wave. Now hit the side of the container again, but much harder (not to the point where you knock over or spill the container). Again, refer to Figure 1. Using the concept of amplitude (or the height of the wave), describe what happens to the wave when you hit the container gently or hard. (In the figure the amplitude changes from column one to column two.)

The amplitude of the wave increases when you hit the container harder.

Step 3: (*Additional background information is included in the Student Instructions.*)

a) Draw a picture showing the physics described in the above paragraph—from hitting the drum to sound reaching the eardrum, through the hammer, to the fluid in the cochlea. Label the following in your picture: pressure, sound waves, eardrum, hammer, anvil, stirrup, cochlea.



Note: Image is not to scale.

b) Pressure is the first stage of physics behind hearing. Pressure (P) is defined as the amount of force (F) per given area (A):

$$P = F/A$$

The amount of pressure is important in hearing because too much can lead to hearing loss. Looking at the equation P = F/A, if force increases, what happens to the pressure?

The pressure increases when the force increases.

Step 4: (*Additional background information and the hair cell cartoon is included in the Student Instructions.*)

a) Hearing is a biological process that bridges the physical and chemical worlds. In Table 2 identify whether the following steps are a physical process, a chemical process, or both simultaneously. Table 1 contains physics and biology concepts you may find helpful.

Step	Physical, Chemical, or Both?
1. Vibrations, or pressure waves, are transmitted through the cochlea to the hair cells	Physical
2. Stereocilia on hair cells move and sway with the vibration	Physical
3. Taller stereocilia pull on a spring to open a "hatch," or channel in the cell (*Figure is included in the Student Instructions*)	Physical
4. Ions, charged particles like sodium (Na^+) and chloride (Cl^-), move through neuron cell channels, changing its electrical potential to produce an electrical charge that moves through the auditory nerve cells to the brain	Both (the chemicals generate the physical electrical charge)
5. The electrical charges reach the end of the neuron, signaling the release of specific chemical neurotransmitters such as dopamine, epinephrine, or other unidentified hearing-specific transmitters	Both (the physical electrical charge triggers the chemicals)
6. The neurotransmitters interact with cells in specific areas of the brain to "hear" and "interpret" the message	Chemical

Step 5: (*Additional information is provided in the Student Instructions.*)

An important step in the scientific process is generating a testable hypothesis. Using information you learned in this lesson so far and the information below, you are going to write your own hypothesis.

Answers will vary. Look for clear communication, correct use of vocabulary and concepts, and specificity in explanations. Students need to back up their reasoning with the processes and information included in this lesson. An example of a minimal response would be "I think the hair cells get damaged because of the higher pressure from the loud sound waves." A more thorough response would be "I think the hair cells get damaged because of the higher pressure from the loud sound waves. That pressure cascades through the ear canal, causing the hair cells to sway excessively and break the 'spring' that opens and closes the ion channel. When the ion channel no longer works, the message does not get sent to the brain."

Authors and Reviewers

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STUDENT INSTRUCTIONS:
The Biophysics of Hearing Loss

Step 1: Read the article "Decibel Hell: The Effects of Living in a Noisy World."

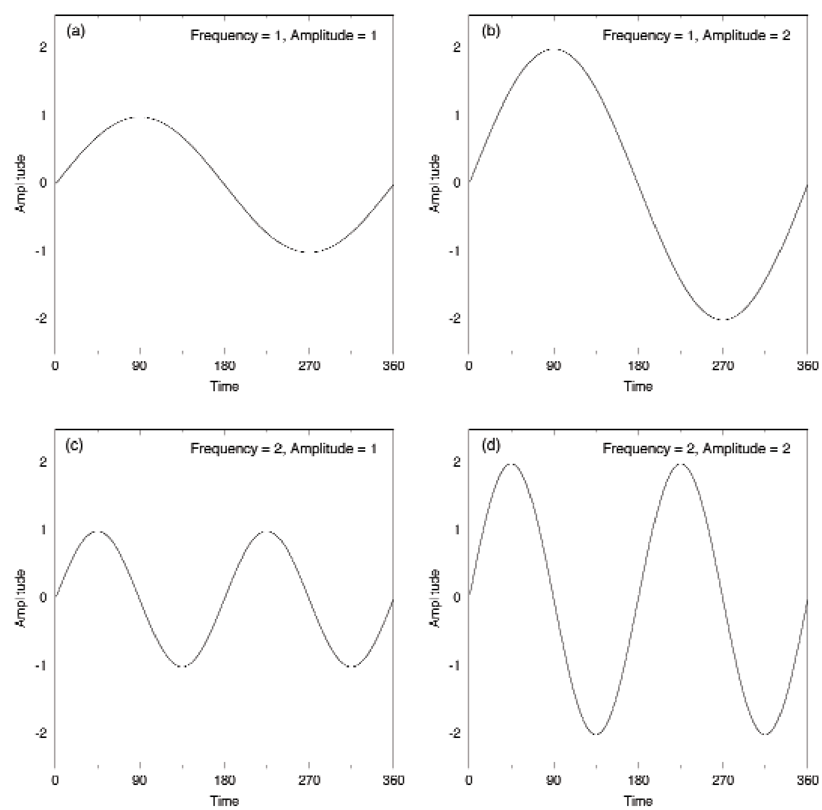
Step 2: Conduct physics demonstrations using a plastic bowl or container, a drumstick (or spoon), and water.

a) Have one person in your group hold the plastic container upside-down, while another person hits the bottom (now the top) moderately hard with a drumstick or spoon. Place your hand inside the container, close to where the drumstick is hitting, but without touching the container. Using the space provided below, describe what you feel. (Rotate roles so that each person has a chance to reach inside the container while someone else is drumming.)

b) Partially fill the container with water (a shallow depth will produce better results). Hold the container so that it does not move, then tap the side of the container slowly. Now tap the side quickly. Using the concept of frequency (see Figure 1, below), describe what happens to the water when you hit the side slowly or quickly. You can think of frequency as the number of waves in a given length of time. (The bottom row of the figure shows a frequency increase compared to the waves in the top row.)

c) Hit the side of the container gently once. Observe the wave. Now hit the side of the container again, but much harder (not to the point where you knock over or spill the container). Again, refer to Figure 1. Using the concept of amplitude (or the height of the wave), describe what happens to the wave when you hit the container gently or hard. (In the figure the amplitude changes from column 1 to column 2.)

Figure 1: Frequency and Amplitude



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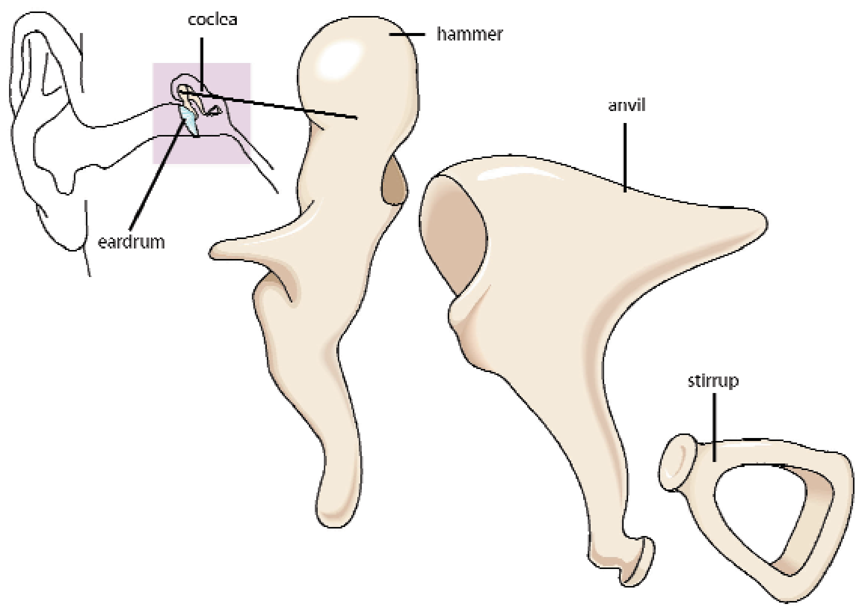
Step 3: Look at Figure 2, below. The main parts we will focus on for this lesson are the eardrum, hammer, anvil, stirrup, fluid, and cochlea.

Figure 2: Diagram of the Inner Ear



Hearing is a biophysical process, where the physical world of sound interacts with the biological world of cells, nerves, and chemical communication. Table 1 below shows some physics concepts related to sound and hearing, as well as some general biological concepts that apply.

The eardrum is called a drum because the ear and a musical drum behave similarly. When pressure changes at different rates (which relates to wave frequency) and strengths (which relates to wave amplitude), waves are generated. For a musical drum, energy is applied through force to the drum by striking the stick to the drumhead. Part of the energy is transmitted to the air and carried as waves via moving air molecules. Those waves then enter the ear canal and apply pressure to the eardrum, which transmits the waves as vibrations through the hammer, anvil, and stirrup. The vibrations are carried into fluid inside the cochlea, which generates waves in the fluid (much like the demonstration you did with the plastic container with water.)

TABLE 1: Physics and Biology Concepts Related to Hearing

Physics	Biology/Biochemistry
Waves Frequency Amplitude Pressure Electricity Energy Force	Cells—hair cells, neurons Chemical communication Physiology—ear canal, eardrum, hammer (bone)

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a) Draw a picture showing the physics described in the above paragraph—from hitting the drum to sound reaching the eardrum, through the hammer, to the fluid in the cochlea. Label the following in your picture: pressure, sound waves, ear canal, eardrum, hammer, anvil, stirrup, waves cause vibrations, cochlea, and waves in fluid.

b) Pressure is the first stage of physics behind hearing. Pressure (P) is defined as the amount of force (F) per given area (A):

$$P = F/A$$

The amount of pressure is important in hearing because too much can lead to hearing loss. Looking at the equation $P = F/A$, if force increases, what happens to the pressure?

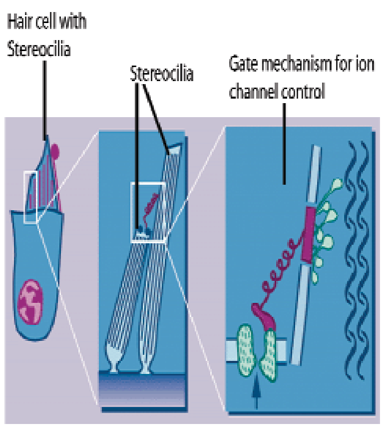
Step 4: So far all of the mechanisms for hearing that we have looked at are physical (i.e., the sound waves traveling through the air into the ear). Biology is the bridge between the physical and chemical world, where living things use physical and chemical processes, such as hearing, for survival.

Now we will look at the cellular level to see how biology translates these physical inputs (sound pressure waves) into electrochemical signals that our brain then interprets—an amazing back-and-forth transition between physics and chemistry. Hair cells with their stereocilia—important players in the hearing process—are found inside the cochlea.

Table 2 outlines some of the biophysical processes in hearing. The discovery of each step was the culmination of many years of work by many different scientists. But there is still much more to learn. Scientists build upon their own work and each others' work to learn more. Then, each time a new discovery is made, new questions are generated; this is the exciting nature of science. Scientific research into the physical and chemical processes involved in hearing will lead to a better understanding of hearing loss and better ways to help people with hearing impairments!

a) Hearing is a biological process that bridges the physical and chemical worlds. In Table 2 identify whether the following steps are a physical process, a chemical process, or both simultaneously. Table 1 contains physics and biology concepts you may find helpful.

TABLE 2: The Biophysics of Hearing

Step	Physical, Chemical, or Both?
1. Vibrations, or pressure waves, are transmitted through the cochlea to the hair cells	
2. Stereocilia on hair cells move and sway with the vibration	
3. Taller stereocilia pull on a spring to open a "hatch," or channel in the cell  **Source:** Image courtesy of Dr. James Hudspeth and the Howard Hughes Medical Institute. Illustration created by Jennifer Jordan/RCW Communications, Inc.	
4. Ions, charged particles like sodium (Na^+) and chloride (Cl^-), move through neuron cell channels, changing its electrical potential to produce an electrical charge that moves through the auditory nerve cells to the brain	
5. The electrical charges reach the end of the neuron, signaling the release of specific chemical neurotransmitters such as dopamine, epinephrine, or other unidentified hearing-specific transmitters	
6. The neurotransmitters interact with cells in specific areas of the brain to "hear" and "interpret" the message	

Step 5: An important step in the scientific process is generating a testable hypothesis. Using information you learned in this lesson so far and the information below, you are going to write your own hypothesis.

The human cochlea only has about 16,000 hair cells, compared to the retina of each eye, which has over 100 million receptors. The concern with having so few hair cells is that, once damaged, they do not regenerate. Based on what you know about the physical and chemical processes of hearing, hypothesize how damage to the hair cells, and thus hearing, can occur from loud noises. Be specific in your hypothesis, using the vocabulary you have learned, and referring to steps in the hearing process and what might happen in those steps to cause damage. Since this is a hypothesis, there is no "right" or "wrong" response. Your hypothesis simply needs to be consistent, thorough, and logical, based on the information you have.